Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

CEMENTATION OF COPPER AND SILVER ON GRANULAR IRON FROM SIMULATED IRON CHLORIDE LEACH SOLUTIONS

D.J. MacKinnon and J.M. Brannen
Metallurgical Chemistry Section
Extractive Metallurgy Laboratory

September 1986

Project: 3.0.52.02
Chloride Processes for Sulphide Ore Treatment

MICROMEDIA

This document is an unedited interim report prepared primarily for discussion and representing a final opinion of the Canada Centre for Mineral and Energy Technology (CANMET)

Ce document est un rapport préliminaire non révisé et rédigé principalement pour fin de discussion et de documentation et représente une opinion définitive du Centre canadien de la technologie des minéraux et de l'énergie (CANMET)

32 pp

MINERAL SCIENCES LABORATORIES
DIVISION REPORT 86-107 (TR)

Crown Copyrights Reserved

CEMENTATION OF COPPER AND SILVER ON GRANULAR IRON FROM SIMULATED IRON CHLORIDE LEACH SOLUTIONS

by

D.J. MacKinnon* and J.M. Brannen**

ABSTRACT

Copper and silver cementation from simulated iron chloride leach solutions on granular iron was studied. The initial cementation rates and the total metal cemented increased with increasing amounts of iron added to the solution, with increasing solution stirring rates and with decreasing HCl concentrations. The rate of copper cementation decreased and the amount of iron consumed increased with increasing Fe^{+3} concentrations in solution. The rates of both copper and silver cementation decreased when the solution contained 50 g/L ferrous chloride.

---

*Research Scientist and **Research Technologist, Mineral Sciences Laboratories, CANMET, Energy, Mines and Resources Canada, 555 Booth Street, Ottawa, Ontario K1A 0G1

CÉMENTATION DU CUIVRE ET DE L'ARGENT SUR DU FER GRENU À PARTIR DE LIQUEURS DE LIXIVIATION SIMULÉES DE CHLORURE DE FER

par

D.J. MacKinnon* et J.M. Brannen**

RÉSUMÉ

On a étudié le procédé de cémentation du cuivre et de l'argent sur du fer grenu à partir de liqueurs de lixiviation simulées de chlorure de fer. Les vitesses initiales de cémentation et la quantité totale de métal cémenté ont augmenté avec l'addition d'une quantité croissante de fer à la solution, avec l'augmentation de la vitesse d'agitation de la solution et enfin, avec la diminution des concentration de HCl. La vitesse de cémentation du cuivre a diminué et la quantité de fer absorbé a augmenté avec l'augmentation des concentrations de Fe^{+3} dans la solution. Les vitesses de cémentation du cuivre et de l'argent ont toutes deux diminué lorsque la solution avait une teneur en chlorure ferreux de 50 g/L.

---

*Chercheur scientifique et **Technologiste de la recherche, Laboratoires des sciences minérales, CANMET, Énergie, Mines et Ressources Canada, 555, rue Booth, Ottawa (Ontario) K1A 0G1.

INTRODUCTION

CANMET is currently investigating a ferric chloride leach process (FCL) for treating the complex sulphide ores of New Brunswick. A proposed flowsheet for the process is shown in Figure 1. For the proposed process to be economically viable, several high-cost unit operations must be modified or replaced by cost effective alternatives. One of the unit operations which requires attention is lead cementation for the removal of copper and silver from the leach solution (see Fig. 1).

A previous study (1) using synthetic leach solutions has shown that a single-stage cementation process employing a 2X stoichiometric quantity of lead dust reduced Cu and Ag to less than 1 mg/L each and within 5 min at 85°C. The cement product from this reaction contained ~50% Pb. Decreasing the amount of lead dust to 1.5X stoichiometric resulted in a product containing ~30% Pb, but the final solution analyzed ~30 mg/L Cu, and this copper concentration could not be reduced by prolonging the cementation time. Further decreases in the stoichiometric amount of lead yielded lower lead contents in the cement product but resulted in higher (~30 mg/L) copper concentrations in the final solution. Incremental addition of the lead dust yielded results similar to a one-step addition. A two-stage cementation reaction with 1:1 stoichiometric lead in the first stage and 1.5X in the second stage resulted in a cement product containing ~70% Cu and 20% Pb, but 15 mg/L Cu remained in the final solution.

The experiments carried out in the previous study (1), although preliminary in nature, suggested that both Cu and Ag could be reduced to <1 mg/L by a single stage cementation process at 85°C using an excess of fine lead dust. Under the preferred conditions, the well-washed cement product contained ~50% Pb, ~40% Cu and ~1% Ag. Furthermore, chemical upgrading of the cement product was possible by leaching it with 4M HCl solution at 80°C to give a final product containing <10% Pb, 70-85% Cu and 1.6-2.6% Ag (1).

Subsequent pilot plant tests using pilot plant leach liquors indicated that 3X stoichiometric lead dust was required to reduce the copper content to 2-3 mg/L; however, during the subsequent filtering operation, some copper redissolved. Thus, it was concluded that further test work was required: 1) to investigate means of improving the efficiency of lead powder cementation,

2) to investigate alternatives to lead powder, and 3) to review process alternatives to produce silver and copper as high value products. The present paper describes the results obtained using granular iron as an alternative to lead powder for cementing Cu and Ag from synthetic FCL leach solutions.

EXPERIMENTAL

The test work was carried out in a vessel containing 300 mL of the desired solution and fitted with a cover designed to hold and position a thermometer and stirrer. The cover also contained an inlet for N_2 gas sparging and a sampling port from which solution was withdrawn at timed intervals for analysis by atomic absorption spectrophotometry. The reaction vessel was placed in a thermostated water bath to maintain the temperature constant, usually at 35°C.

The solution consisted of 3.0M NaCl + 0.3M HCl and contained 1.0 g/L Cu^{2+} and 0.02 g/L Ag^{+}. The variables investigated were: the amount of granular iron added, temperature, stirring speed, the effect of Fe^{3+}, the effect of HCl, the effect of Fe^{2+} and the effect of $PbCl_2$. The tests were run for one hour.

RESULTS AND DISCUSSION

1. Effect of the Amount of Added Iron

The effect of the amount of added iron on copper and silver cementation was determined using a solution containing 3.0M NaCl + 0.3M HCl, 1.3 g/L Cu^{2+} and 0.0187 g/L Ag^{+} at 35°C and 500 RPM. The results obtained using 0.3 g (0.9X stoichiometric), 0.6 g (1.8X stoichiometric) and 1.10 g (3.1X stoichiometric) granular iron are shown in Figures 2 and 3 as copper and silver concentration vs time plots.

As indicated in Figure 2, both the initial cementation rate and the amount of Cu cemented increase with increasing amounts of iron added to the solution. At 0.9X stoichiometric iron, all the copper is not cemented; the maximum Cu cemented is reached after 20 minutes with 0.4 g/L Cu remaining in solution. At 1.8X stoichiometric Fe, the maximum amount of Cu cemented

again occurs at 20 minutes with ≈0.04 g/L Cu remaining in solution. At 3.1X stoichiometric iron only a few mg/L Cu remains in solution after 20 minutes.

Figure 3 indicates that the initial rate of silver cementation also increased with increasing amounts of iron added to the solution. The amount of silver remaining in solution was 0.2 mg/L; this Ag level was attained after $\leq$30 minutes depending on the amount of iron added.

As indicated in Figures 4 and 5, the initial rates of copper and silver cementation both increase linearly with increasing amounts of added iron. This suggests a constant initial rate per unit area of iron. Whereas the initial rate of copper cementation appears to be directly proportional to the surface area of the granular iron (Figure 4), that for silver is not, (cf. Figure 4 and 5). This apparent anomalous behaviour of silver may be due to the relatively low concentration of silver in the solution.

The total iron dissolved after 60 minutes was determined by chemical analysis of the final filtered cementation solution. The results are presented in Figure 6 as a plot of iron dissolved vs the amount of iron metal added to the solution. The results show that there is a linear increase in iron dissolution with increasing amounts of added iron metal. The stoichiometric amount of iron required to cement the copper and silver from solution was calculated based on the reactions:

$$Cu^{2+} + Fe^{0} = Fe^{2+} + Cu^{0}$$

$$2Ag^{+} + Fe^{0} = Fe^{2+} + 2Ag^{0}$$

The difference between the stoichiometric and the actual iron dissolved gives the excess iron consumed in the reactions and this is also indicated in Figure 6.

Chemical analysis of the initial standard cementation solution indicated 10.13 g/L HCl (≈0.3M HCl). The final cementation solution (after 60 minutes) was analysed for the HCl concentration. The results, Figure 7, also indicate that HCl consumption increased linearly with increasing amounts of added iron metal.

2. Effect of RPM

The effect of stirring speed, RPM, on the cementation of copper and silver on granular iron was studied at 35°C using 0.45 g iron; i.e., ≈1.3X stoichiometric. The initial rates of copper and silver cementation were determined from the slopes of the respective metal ion concentration vs time plots over the range 50 to 1000 RPM; i.e.; from 5.2 to 104.7 radians/s. The results are shown in Figures 8 and 9 as plots of initial rate vs $\omega^{\frac{1}{2}}$. The results obtained for both copper and silver, Figures 8 and 9 respectively, indicate a sharp increase in the initial rate for RPM >500; i.e.; >52.4 radians/s.

At the lowest stirring speed, 50 RPM, a significant amount of copper and silver remained in solution; i.e., 0.400 g/L and 4.8 mg/L, respectively, after 60 minutes. The lowest concentration of copper remaining in solution, 0.004 g/L, occurred at 750 RPM. Hence, this was the stirring speed chosen to study the remaining variables.

The morphologies of the Cu-Ag-Fe cement products obtained at 500 and 1000 RPM are compared in the SEM photomicrographs, Figure 10. The similarity in the morphologies of the two deposits suggests that the observed increase in the initial reaction rate for RPM >500 cannot be attributed to changes in the deposit morphology. The sharp increase in the initial cementation rates observed for RPM >500 is probably due to more effective mixing of the granular iron with the solution; i.e., the granular iron is not completely suspended at the lower stirring speeds.

At RPM $\leq$250, less than the stoichiometric amount of iron dissolved during reaction, and this is in agreement with the substantial amount of Cu remaining in solution. At RPM >250, the amount of iron dissolved was relatively constant, having an average value of about 1.32 g/L Fe. The average amount of HCl consumed during the RPM study was 1.3 g/L.

3. Effect of Temperature

The effect of temperature in the range 25-80°C on the cementation of copper and silver on granular iron was determined at 750 RPM using 0.45 g (1.3X stoichiometric) iron. The initial rates of copper and silver cementation were determined from the slopes of the metal ion concentration vs time plots, and the results are presented in the Arrhenius plots shown in Figures 11 and 12. The values of the activation energy for copper and

silver cementation, 3.1 and 2.9 K_{cal}/mole, respectively, suggest that the reaction is diffusion controlled.

The initial rates of copper and silver cementation increased from 0.14 to 0.30 g Cu/L/min and from 2.6 to 6.2 mg Ag/L/min over the temperature interval from 25 to 80°C. The iron consumption increased from 1.36 g/L at 25°C to 1.68 g/L at 80°C, equivalent to 0.19 and 0.51 g/L excess iron, respectively. The average acid consumption over this temperature range was 0.91 g/L. At temperatures >60°C, the amount of copper remaining in solution after 60 minutes increased, possibly due to re-solution of cemented copper. At temperatures <60°C, the average amount of copper remaining in solution was 0.003 g/L.

4. The Effect of Ferric Ion Concentration

The presence of ferric ion in the cementation solution results in excess iron consumption either directly by reaction with iron; i.e.,

$$2Fe^{3+} + Fe^{0} = 3Fe^{2+}$$

or indirectly by reaction with cemented copper; i.e.,

$$2Fe^{3+} + Cu^{0} = Cu^{2+} + 2Fe^{2+}$$

The effect of ferric ion concentration on the cementation of copper and silver was studied at 35°C and 750 RPM using 0.45 g Fe (1.3X stoichiometric). The results obtained over the ferric ion concentration range 0-1 g/L are shown in a series of copper concentration vs. time plots in Figure 13. The influence of ferric ion is noticeable after about 2.5-3 minutes. As the concentration of ferric ion in solution increases, the efficiency of copper cementation deceases. Figure 14 shows a plot of the amount of copper remaining in solution after 60 minutes vs. the initial ferric ion concentration of the solution. At 0.5 g/L Fe^{3+}, there is an abrupt increase in the copper content of the final cementation solution. This arises because 0.45 g Fe is the stoichiometric equivalent required to reduce the Cu^{2+}, Ag^{+} and Fe^{3+} contained in the solution. For Fe^{3+} >0.5 g/L, the excess Fe^{3+} is reduced preferentially to Cu^{2+} and, hence, the Cu^{2+} concentration in the final solution increases. This was confirmed by

varying the amount of Fe added to the solution while maintaining the Fe^{3+} concentration constant at 0.5 g/L. The results are shown in Figure 15 as a plot of copper remaining in solution vs. grams of added iron. The residual copper remaining in solution decreases rapidly with an increase in the amount of added iron until the stoichiometric amount of iron is present. Thereafter, a low and nearly constant final copper concentration is observed.

The presence of ferric ion in solution also increased the HCl consumption from 1.16 g/L at 0 g/L Fe^{3+} to 2.33 g/L at 1.0 g/L Fe^{3+}. The final Ag^{+} concentration in solution was not significantly changed by the presence of Fe^{3+} under these experimental conditions.

5. The Effect of the HCl Concentration

The effect of the initial HCl concentration on the cementation of copper and silver on granular iron (0.45 g) was determined at 35°C and 750 RPM. The results, presented in Table 1, show that the initial rates of both Cu and Ag cementation decrease with increasing HCl concentration to about 0.3M HCl, but are independent of higher HCl concentrations.

Table 1. The effect of HCl concentration on the initial rates of Cu and Ag cementation on 0.45 g Fe at 35°C and 750 RPM

	INITIAL RATE	
HCl (M)	Cu (g/L/min)	Ag (mg/L/min)
0.05	0.31	4.8
0.10	0.24	4.3
0.30	0.16	3.5
0.40	0.16	3.5
0.50	0.16	3.5

6. The Effect of the Form of Iron

The cementation of copper and silver on various forms of iron was studied at 35°C and 500 RPM using 0.45 g each of granular iron, iron filings and reduced iron powder. The results are presented in Figures 16 and 17 as plots of copper and silver concentration vs. time. As indicated, the initial rates of both copper and silver cementation (see also Table 2) increased in the order filings < granular < reduced powder. The observed

Table 2. Effect of the form of iron on the initial cementation rates of copper and silver at 35°C, 500 RPM and 0.45 g Fe

Iron (Form)	INITIAL RATE Cu (g/L/min)	Ag (mg/L/min)
Filings	0.024	0.25
Granular	0.10	1.8
Powder	0.25	9.0

variation in the initial cementation rates is probably related to differences in the surface areas of the various types of iron. The slowest rates were observed for the iron filings which were the coarsest of the three forms of iron, whereas the reduced powder (finest size) gave the fastest rates. The initial rate of silver cementation seems to be more dependent on the form of the iron than does the rate for copper cementation. This may be due to the relatively low concentration of silver in the solution.

For the iron filings 0.40 g/L Cu remained in solution after 60 minutes, whereas 0.005 g/L Cu remained in solution for both the granular iron and the reduced powder.

7. The Effect of Ferrous Chloride and Lead Chloride Concentrations

Since process leach liquors will contain high concentrations of both ferrous chloride and lead chloride, the effect of these species on the cementation of Cu and Ag on granular iron was examined briefly. The results obtained for the effect of 50 g/L ferrous chloride on the initial rate of Cu and Ag cementation for two levels of granular iron (0.45 and 1.1 g) are presented in Table 3. The presence of 50 g/L ferrous chloride results in a decrease in the initial rate of both Cu and Ag cementation. This observation suggests that the reaction rate may be controlled by the diffusion of ferrous ions or an iron-chloro complex species away from the reaction surface. A more detailed study on the effect of ferrous chloride concentration would be required to confirm this point. For 1.1 g Fe, in the absence of ferrous chloride, all the Cu is cemented after 5 minutes; in the

Table 3. The effect of ferrous chloride and lead chloride concentrations on the initial rates of copper and silver cementation on granular iron at 35°C and 750 RPM

Fe° (g)	Ferrous Chloride (g/L)	Lead Chloride (g/L)	INITIAL RATE Cu (g/L/min)	INITIAL RATE Ag (mg/L/min)
0.45	0	0	0.16	3.8
	50	0	0.07	3.0
	0	5	0.16	3.8
1.1	0	0	0.32	9.9
	50	0	0.13	5.8

presence of 50 g/L ferrous chloride, all the Cu is cemented after 20 minutes. The presence of 5 g/L lead chloride has no effect on the initial rate of either Cu or Ag cementation on granular iron.

8. Residue Analysis

Selected residues were analysed for their Cu and Fe contents, and the results are shown in Table 4. As expected, the percentage of iron in the residue increases with increasing amounts of Fe added to the solution. At 1.3X stoichiometric granular iron, the copper content of the solution is reduced to <10 mg/L after 20 minutes and the cement product is about 80% Cu and 15% Fe.

Table 4. The effect of the amount of added Fe on the composition of the cement residue at 35°C and 500 RPM

Fe (g)	Stoichiometric	RESIDUE Cu (%)	RESIDUE Fe (%)
0.30	0.9X	89	1.6
0.45	1.3X	81	14
0.90	2.6X	41	49
1.35	3.8X	28	63

CONCLUSIONS

The cementation of copper and silver on iron from simulated iron chloride leach solutions has been studied over a range of experimental conditions. Increasing the active surface area of the cementing metal, either by increasing the amount of metal or by using different size fractions of the metal, increases the initial rates of both copper and silver cementation. The rates of copper and silver cementation on granular iron at 35°C increase rapidly when the solution is stirred at >500 RPM. Increasing temperatures result in only moderate increases in the initial cementation rate.

Decreasing the HCl concentration from 0.3M to 0.05M results in an increase in the initial rates of copper and silver cementation on granular iron. The initial cementation rates are not affected by increasing HCl concentrations above 0.3M; i.e., to 0.5M. The presence of 50 g/L ferrous chloride in the solution results in a substantial decrease in the initial cementation rate and consequently an increase in the time required to cement >99% of the copper and silver from solution. The initial cementation rates are not influenced by the presence of 5 g/L $PbCl_2$ in the solution.

Iron consumption is slightly greater than the stoichiometric amount required to precipitate all the copper and silver from solution. The amount of excess iron consumed increases with increasing amounts of iron added to the solution, with increasing temperature and with increasing RPM. Increasing HCl concentrations did not significantly increase the excess iron consumed. The HCl consumption is usually about 1.3 g/L, but the amount increases with increasing amounts of iron added to the solution. As expected, the presence of Fe^{+3} in the solution subtantially increases the consumption of iron.

ACKNOWLEDGEMENT

The SEM photomicrographs of the cement products were taken by D. Owens.

REFERENCES

1. MacKinnon, D.J., Dutrizac, J.E. and Hardy, D.J. "Cementation of Silver and Copper on Lead Dust and Chemical Upgrading of the Cement Product"; Division Report MRP/MSL 85-86 (TR); CANMET, Energy, Mines and Resources Canada; Ottawa; 1985.

FIGURE CAPTIONS

Fig. 1 - Proposed two-stage ferric chloride leach process flowsheet.

Fig. 2 - Plots showing the decrease of copper concentration with time as a function of the amount of granular iron added to a solution containing 3.0M NaCl + 0.3M HCl at 35°C; 500 RPM.

Fig. 3 - Plots showing the decrease of silver concentration with time as a function of the amount of granular iron added to a solution containing 3.0 M NaCl + 0.3M HCl at 35°C; 500 RPM.

Fig. 4 - Plot showing the increase in the initial rate of copper cementation as a function of the amount of granular iron added to a solution containing 3.0M NaCl + 0.3M HCl at 35°C; 500 RPM.

Fig. 5 - Plot showing the increase in the initial rate of silver cementation as a function of the amount of granular iron added to a solution containing 3.0M NaCl + 0.3M HCl at 35°C; 500 RPM.

Fig. 6 - Plots showing the increase in the total and excess iron dissolved as a function of the amount of granular iron added to a solution containing 3.0M NaCl + 0.3M HCl at 35°C; 500 RPM.

Fig. 7 - Plot showing the increase in HCl consumption as a function of the amount of granular iron added to a solution containing 3.0M NaCl + 0.3M HCl at 35°C; 500 RPM.

Fig. 8 - Plot showing the increase in the initial rate of copper cementation on 0.45 g granular iron as a function of stirring rate; 3.0M NaCl + 0.3M HCl; 35°C.

Fig. 9 - Plot showing the increase in the initial rate of silver cementation on 0.45 g granular iron as a function of stirring rate; 3.0M NaCl + 0.3M HCl; 35°C.

Fig. 10 - SEM photomicrographs showing the morphology of the Cu/Ag cement product on 0.45 g granular iron obtained at a) 500 RPM and b) 1000 RPM; 3.0M NaCl + 0.3M HCl; 35°C.

Fig. 11 - Arrhenius plot obtained for copper cementation on 0.45 g granular iron; 3.0M NaCl + 0.3M HCl; 750 RPM.

Fig. 12 - Arrhenius plot obtained for silver cementation on 0.45 g granular iron; 3.0M NaCl + 0.3M HCl; 750 RPM.

Fig. 13 - Plots showing the variation of the residual copper concentration with time as a function of the Fe^{+3} concentration; 3.0M NaCl + 0.3M HCl, 0.45 g granular iron; 35°C; 750 RPM.

Fig. 14 - Plots showing the variation of the residual copper remaining in solution and HCl consumption as a function of Fe^{+3} concentration; 3.0M NaCl + 0.3M HCl; 0.45 g granular iron; 35°C; 750 RPM.

Fig. 15 - Plot showing the effect of increasing amounts of granular iron on the residual copper remaining in solution at 0.5 g/L Fe^{3+}; 3.0M NaCl + 0.3M HCl; 35°C; 750 RPM.

Fig. 16 - Plots showing the variation in copper concentration as a function of the form of iron (0.45 g) added to a solution containing 3.0M NaCl + 0.3M HCl; 35°C; 500 RPM.

Fig. 17 - Plots showing the variation in silver concentration as a function of the form of iron (0.45 g) added to a solution containing 3.0M NaCl + 0.3M HCl; 35°C; 500 RPM.

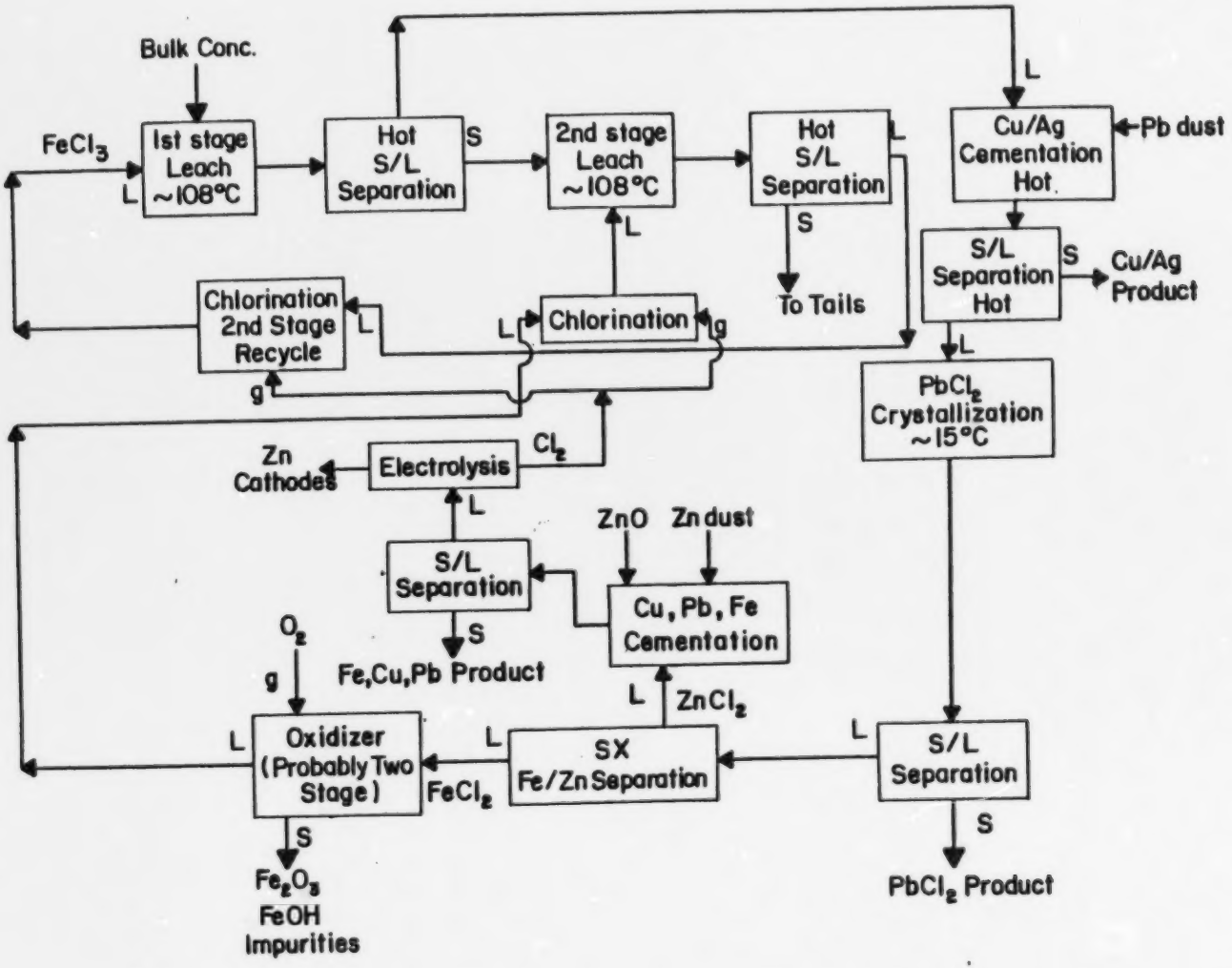


Figure 1 Proposed Two-Stage Ferric Chloride Leach Process Flowsheet

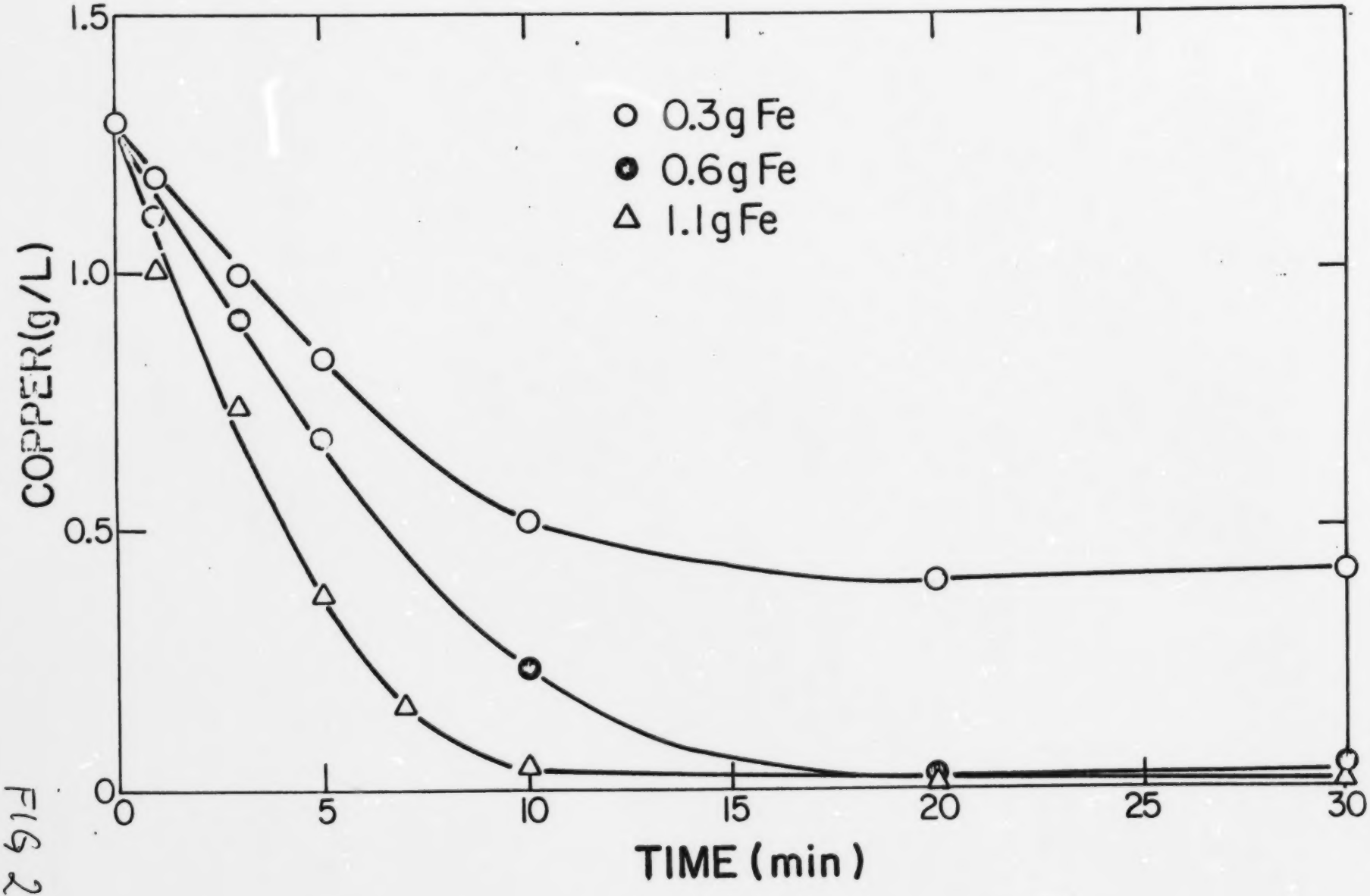


FIG 2

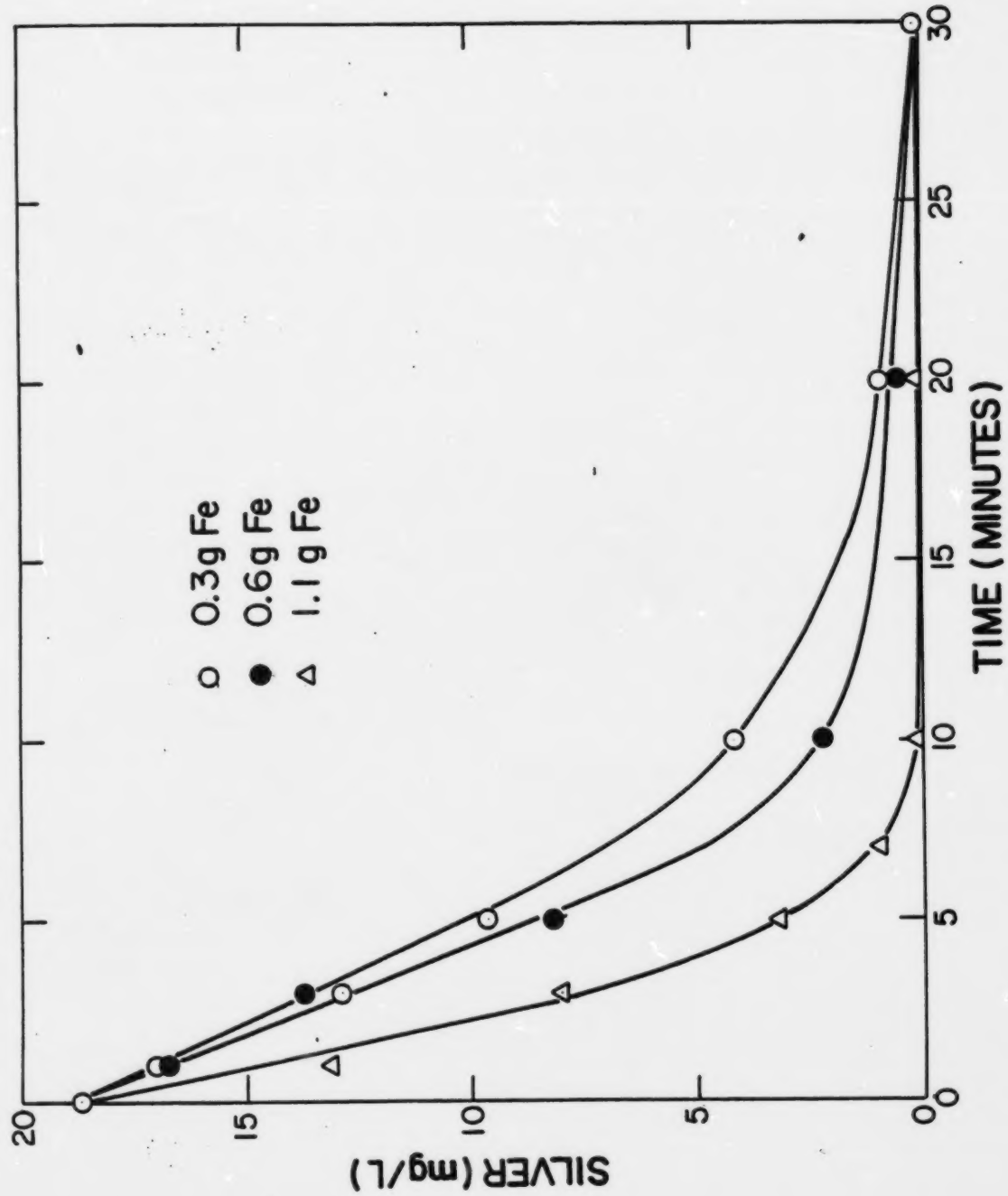


FIG 3

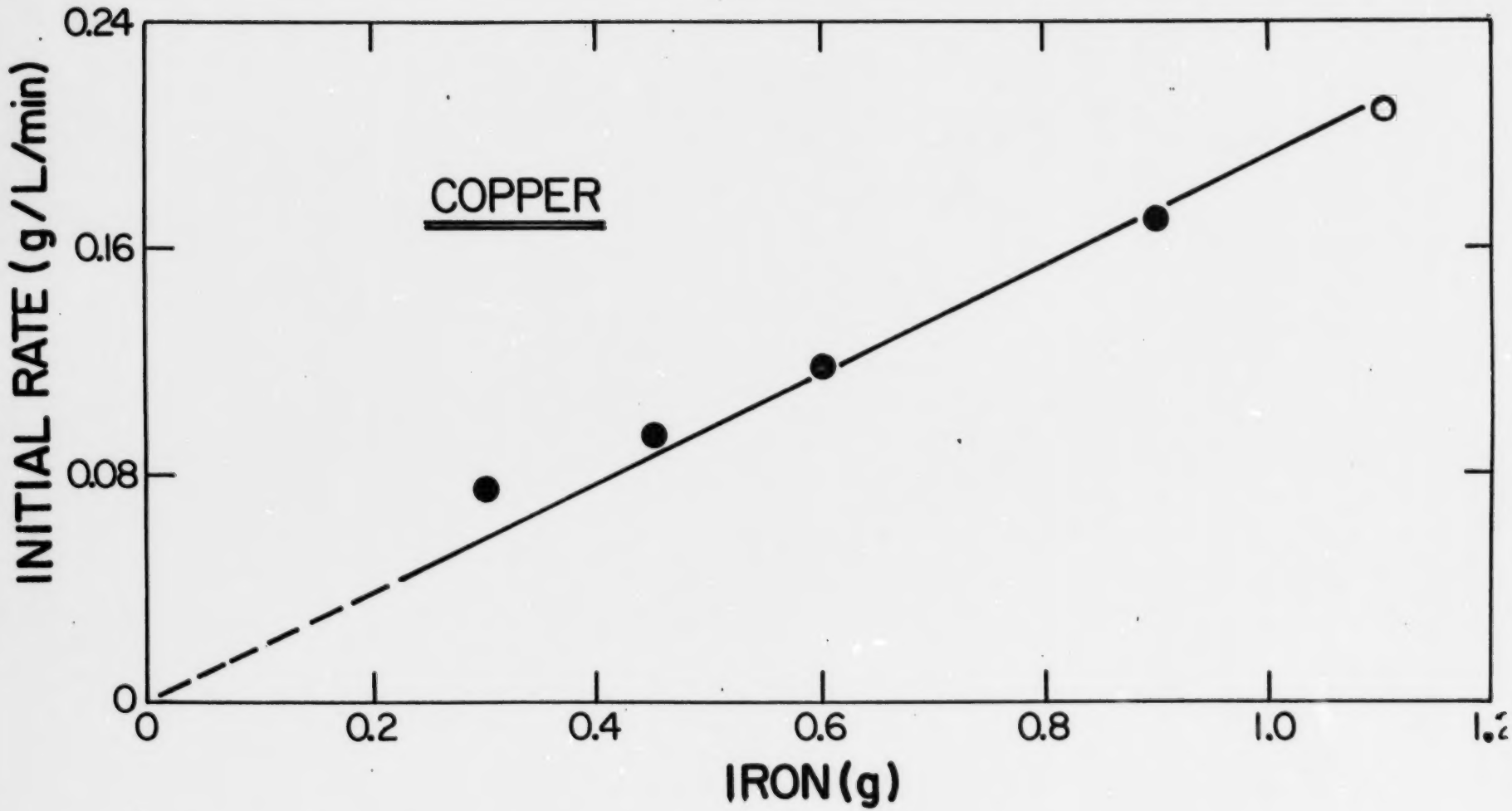
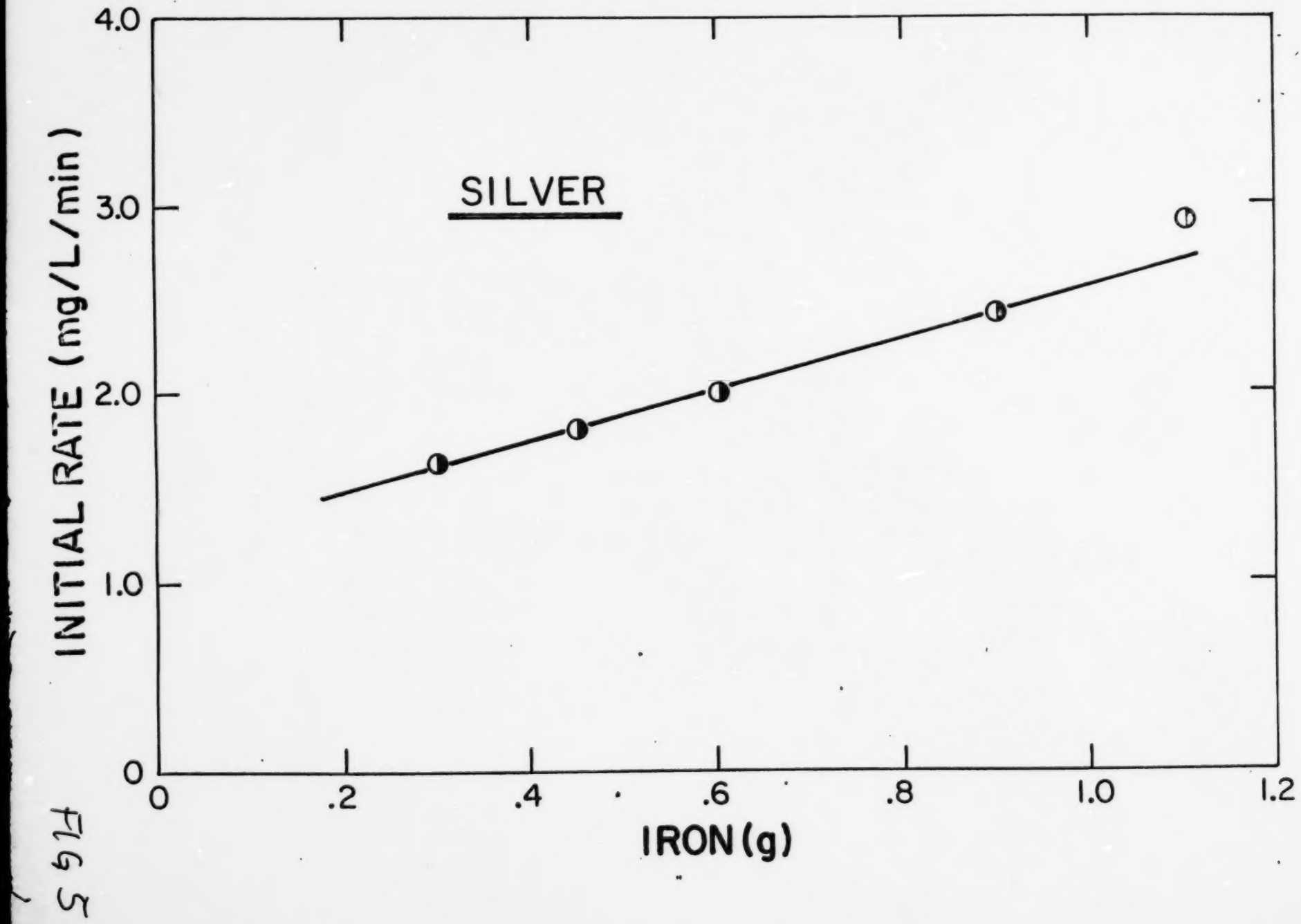


FIG 4



S 514

EXCESS Fe DISSOLVED (g/L)
2.0
1.6
1.2
0.8
0.4
1.6
1.2
0.8
0.4
0
IRON (g)
X = Stoichiometric
IRON DISSOLVED (g/L)
2.0
1.6
1.2
0.8
0.4
0

FIG 6

FIG 7

INITIAL RATE (g/L/min)
0.3
0.2
0.1
0
0
4
8
12
$\omega^{\frac{1}{2}}$ ($s^{-\frac{1}{2}}$)
COPPER

FIG 8

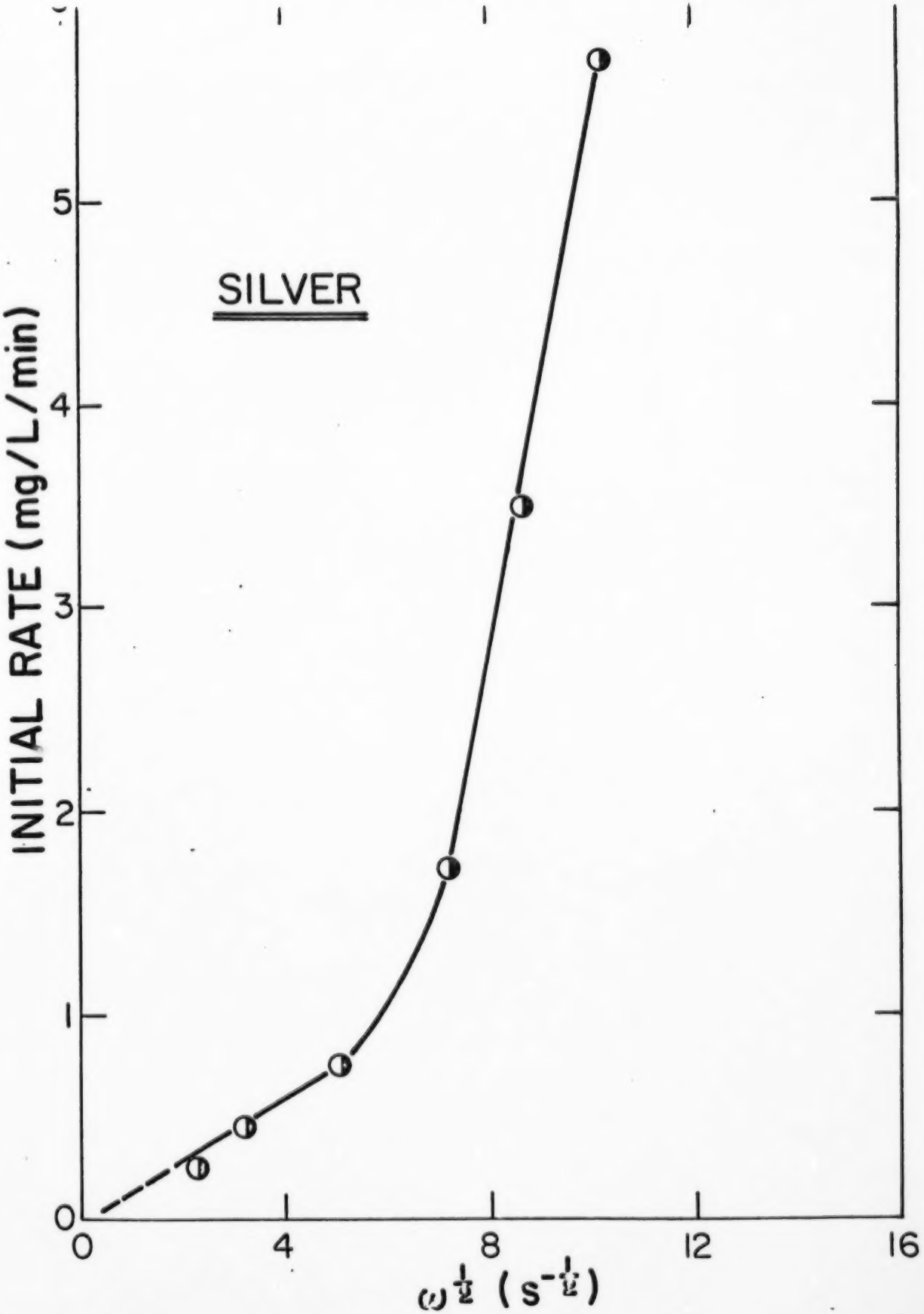
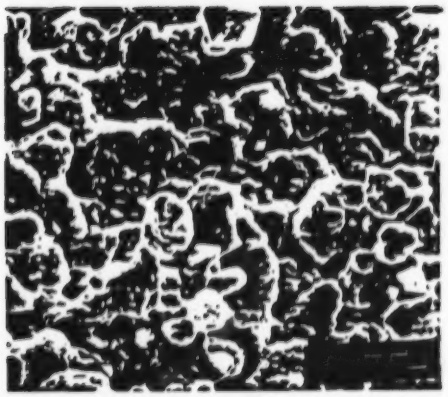
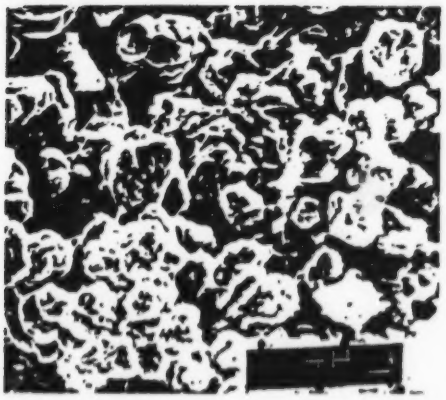

SILVER
INITIAL RATE (mg/L/min)
0
1
2
3
4
5
0
4
8
12
16
$\omega^{\frac{1}{2}}$ ($s^{-\frac{1}{2}}$)

FIG 9

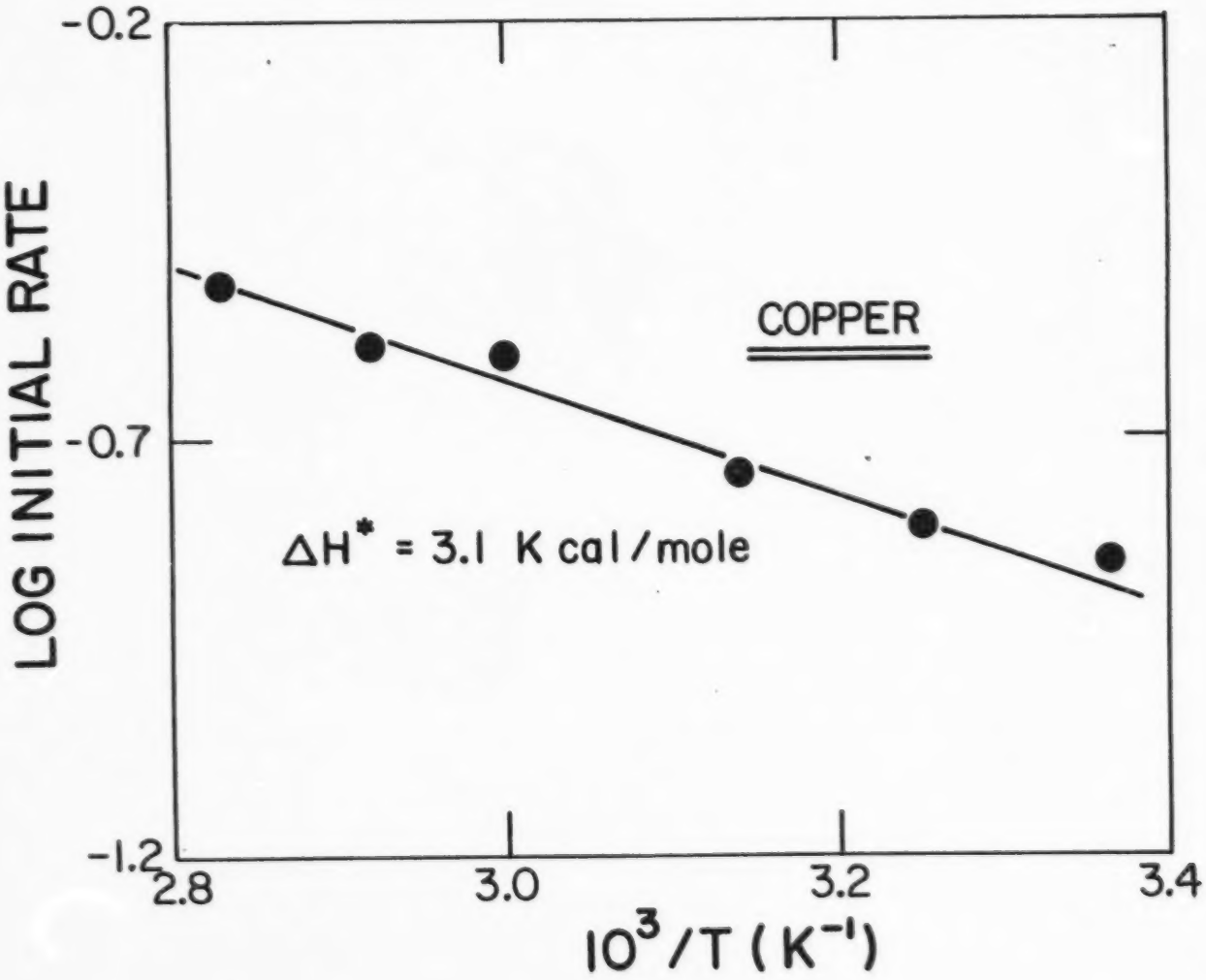


a) 500 RPM



b) 1000 RPM

Figure 10. Morphology of the Cu/Ag cement product on 0.45g granular iron obtained at a) 500RPM and b) 1000 RPM; 3.0M NaCl + 0.3M HCl; 35°C.


-0.2
-0.7
-1.2
LOG INITIAL RATE
COPPER
ΔH* = 3.1 K cal / mole
2.8
3.0
3.2
3.4
10³/T (K⁻¹)

F16 11

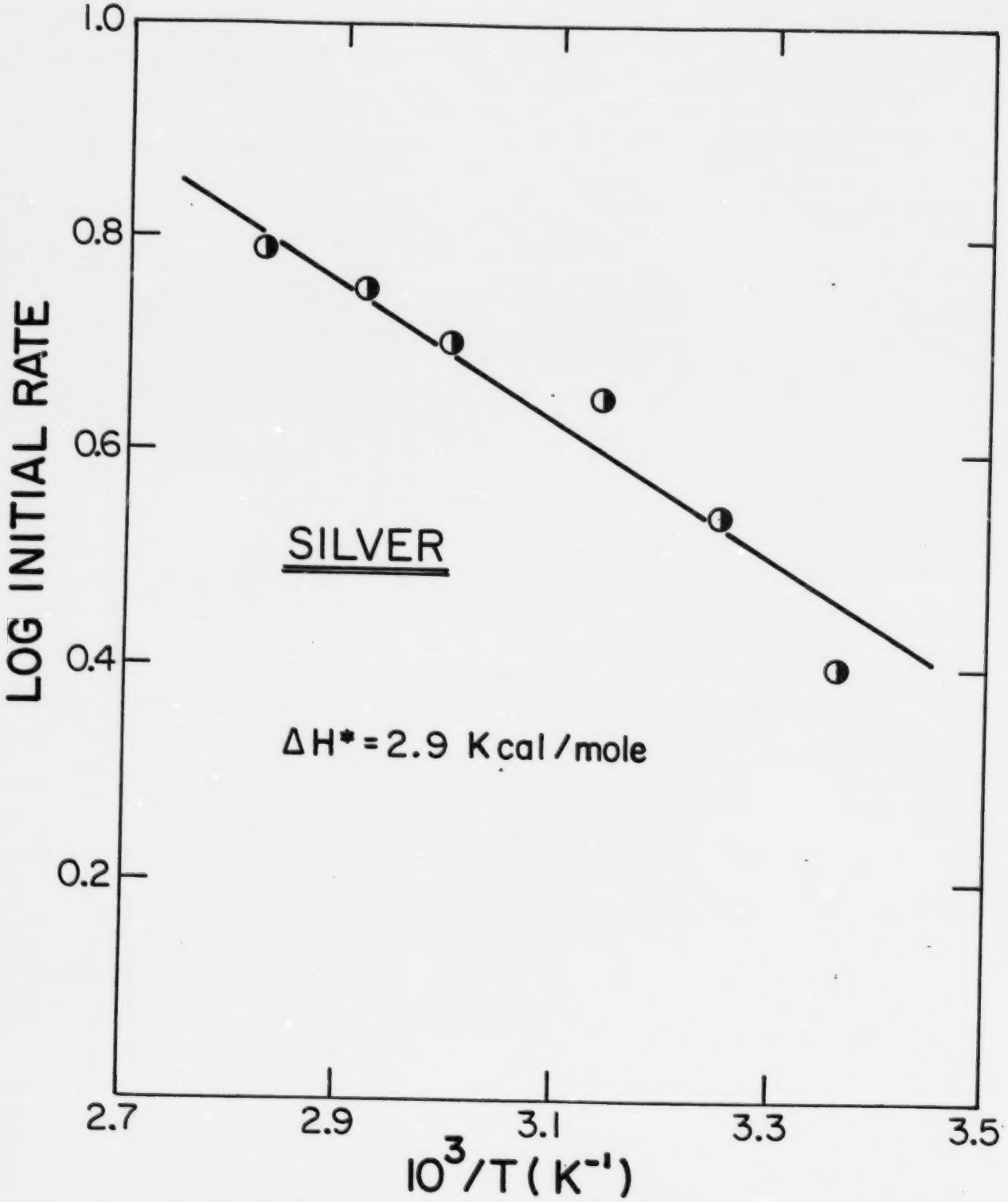

1.0
0.8
0.6
0.4
0.2
LOG INITIAL RATE
SILVER
ΔH* = 2.9 Kcal / mole
2.7
2.9
3.1
3.3
3.5
10³/T (K⁻¹)

FIG 12

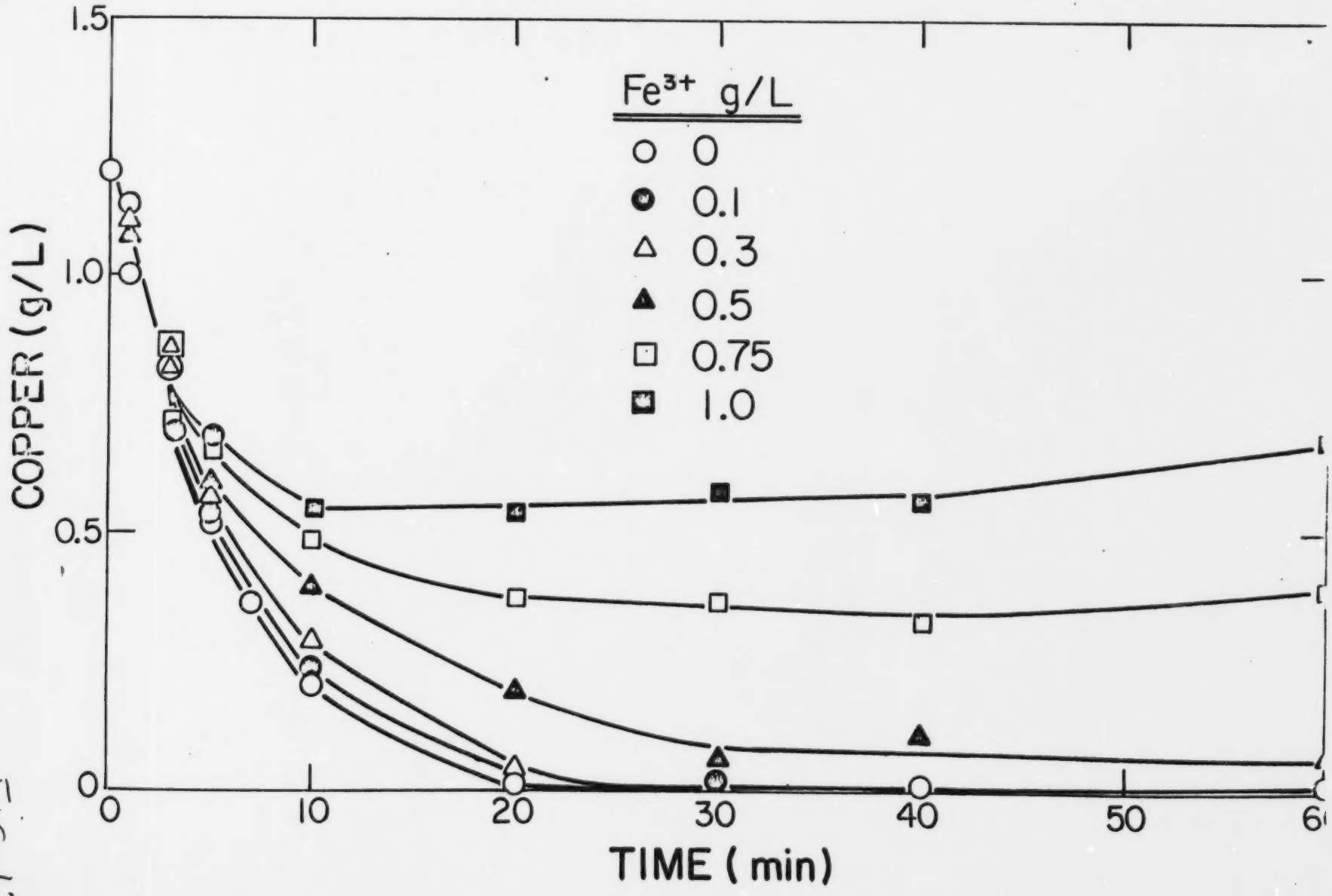

1.5
1.0
0.5
0
COPPER (g/L)
Fe3+ g/L
0
0.1
0.3
0.5
0.75
1.0
0
10
20
30
40
50
TIME (min)

FIG 13

HCl CONSUMPTION (g/L)
3.0
2.0
1.0
0
1.0
0.8
0.6
0.4
0.2
0
Fe^{+3}(g/L)
RESIDUAL COPPER (g/L)
0.75
0.50
0.25
0

FIG 14

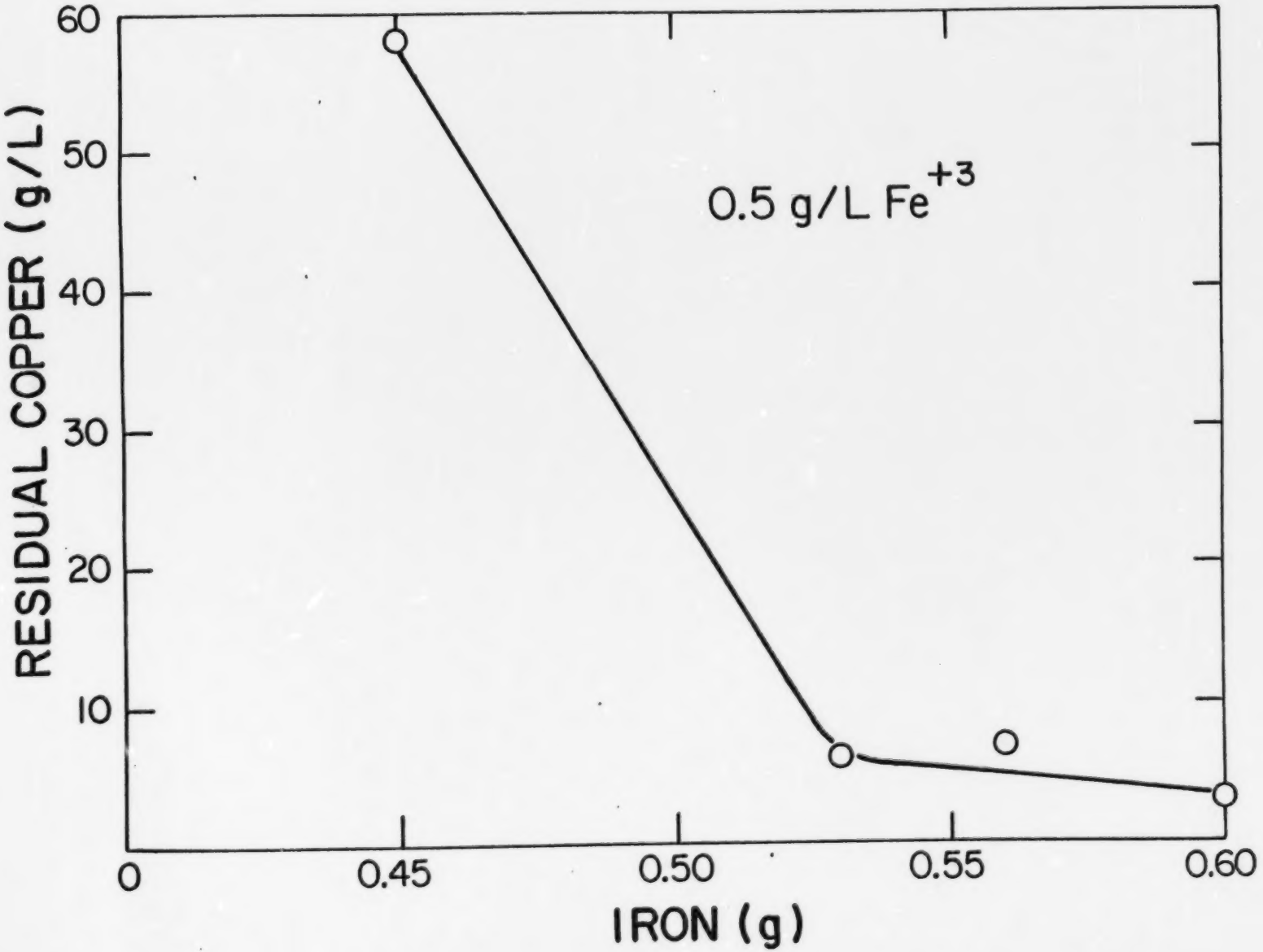
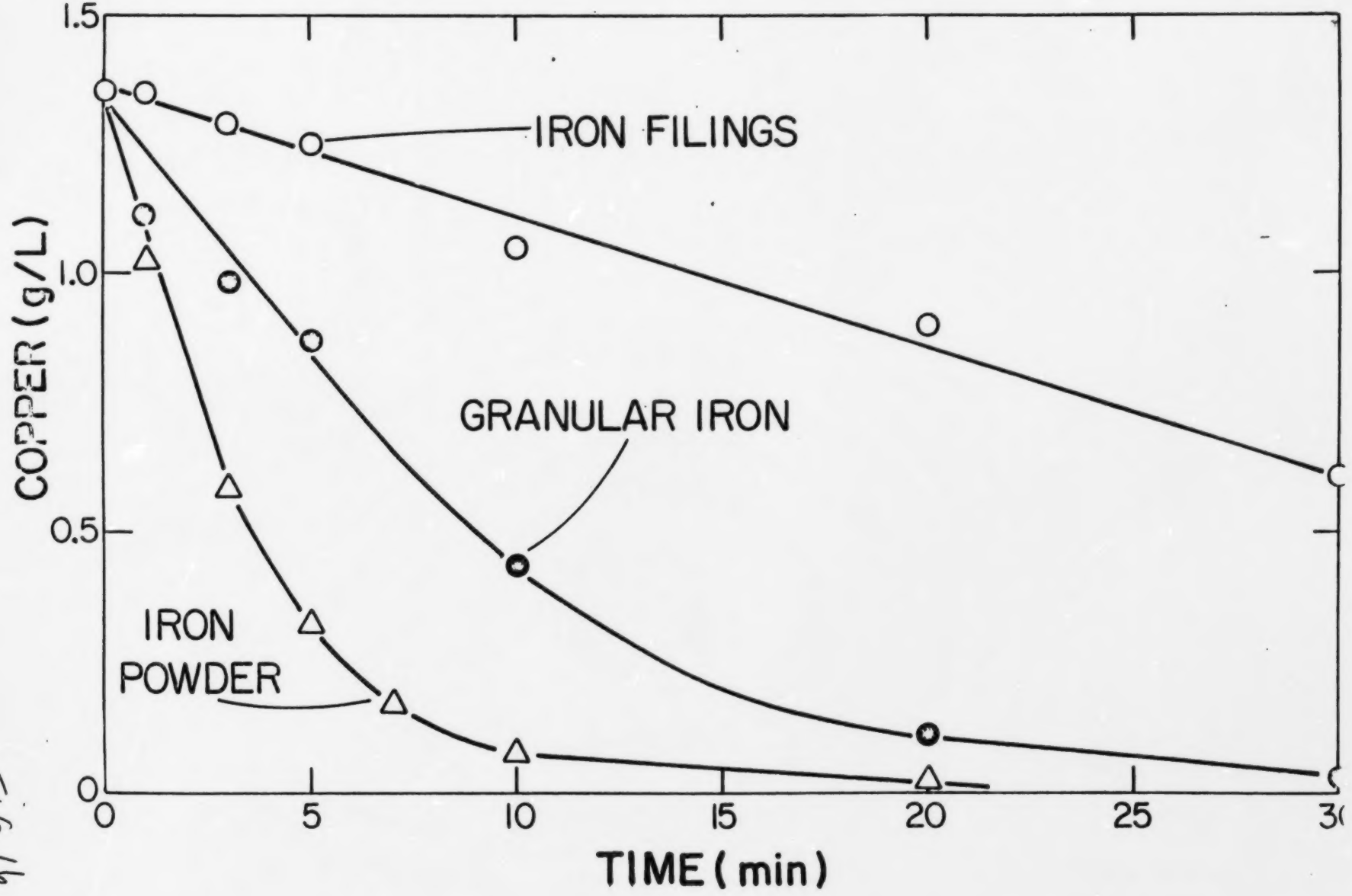

RESIDUAL COPPER (g/L)
60
50
40
30
20
10
0
0.45
0.50
0.55
0.60
IRON (g)
0.5 g/L Fe+3

Fig 15


1.5
1.0
0.5
0
COPPER (g/L)
IRON FILINGS
GRANULAR IRON
IRON
POWDER
0
5
10
15
20
25
TIME (min)

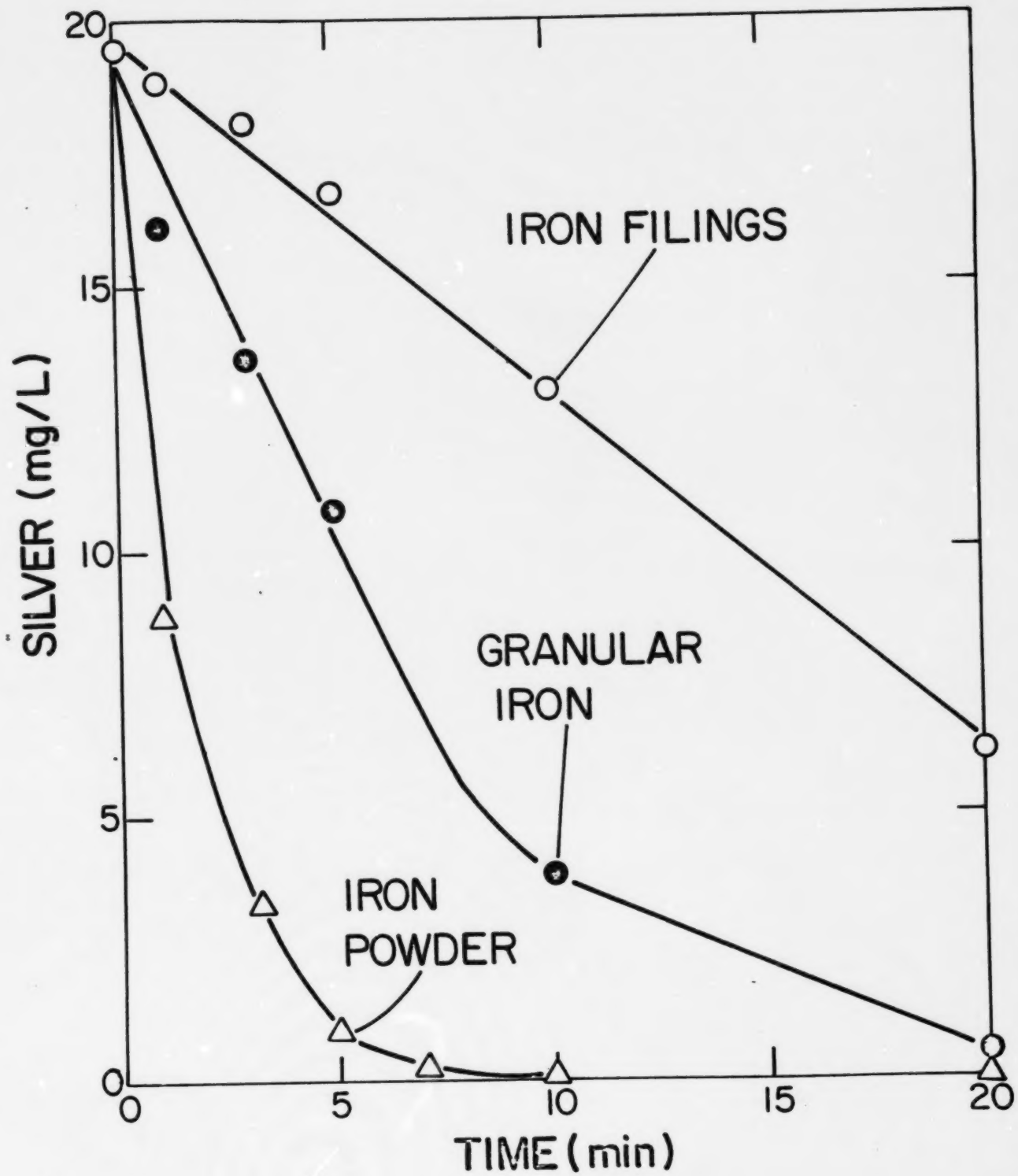

20
15
10
5
0
0
5
10
15
20
SILVER (mg/L)
TIME (min)
IRON FILINGS
GRANULAR IRON
IRON POWDER

FIG 17